THE DESIGN AND ANALYSIS OF A MULTI-STAGE MEATGRINDER CIRCUIT

D. Giorgi, K. Lindner, J. Long, T. Navapanich, O. Zucker
Energy Compression Research Corp.
2043 De Mayo Rd., Del Mar Ca. 92014

ABSTRACT

This paper describes the determination of design requirements, performance analysis and design tools used in the design of an 11-step high efficiency high current gain device at the multi-megajoule energy level. In addition to the efficiency improvement when compared with the conventional approach, the total switch power (ie., current x voltage) is reduced from twice the load power to roughly 1/3 the load power. The individual switch power is reduced to 1/18 the load power.

INTRODUCTION

The practical use of the Meatgrinder[1] circuit for transferring energy to an uncoupled load inductor requires a design that will provide the necessary mutual inductance, have an adequate L/R time, and be able to hold the voltages generated in the transfer process. The specific design requirements depend on the application. Some applications require large current gain in addition to efficient energy transfer. Other applications are concerned with improving the match between an existing opening switch and a given load requirement.

THE PROBLEM

Many high power applications face the common problem of inefficient energy storage and transfer to an inductive load. In conventional high power applications, a flywheel-Homopolar Generator (HPG) is used to perform three separate tasks: i) mechanical to electrical conversion, ii) current multiplication (from kA to MA), and iii) time compression (energy delivery from many seconds to roughly 0.1 sec). However, this time compression falls short of the demands of many applications such as the SDI Electro-Magnetic Gun which requires 1-10 ms to energize the gun. Consequently, an inductive store is used as an intermediate stage. One can power the inductors directly from an alternator or batteries but the inductor time constant is usually too short and the current multiplication required in the inductive store by transformer action is too inefficient.

Applications requiring high energy (greater than 50 MJ) with repetition rates (more than 1 pps) increase the required size of the inductive store, and thus its inherent time constant, while simultaneously reduce the <u>required</u> time constant to only a few seconds. The time constant and stored energy vs. major radius (Figure 1) for a toroidal room temperature copper inductor shows that at radius R = 1.50 m, the coil stores 50 MJ and its time constant is ~3.5 seconds. Thus the coil can be energized in approximately 1 second (1 pps) with a small loss of energy (for higher repetition rates, 1 second time constant will suffice).

Next, the energy transfer system is required to multiply current since it is desirable to energize the coil from an efficient alternator (10 kA, 5-10 kV) but provide in excess of 1 MA to the inductive load. This can be done by configuring the coil as a conventional transformer. However, it is easily shown that such transformations and transfer to the load are both lossy and suffer from severe high voltage problems in the primary.

THE SOLUTION

The "Meatgrinder" circuit (see Figure 2) described below offers a viable solution to the transfer of energy to an inductive load. The Meatgrinder is an inductive energy transfer circuit under development by ARDC, that can act as a current multiplier, storage, and transfer element concurrently in this situation. The Meatgrinder approach uses a modified storage inductor with multiple taps and sequential switching to transfer the energy in a series of steps. This arrangement simultaneously provides for both current multiplication through transformer action with initial conditions and energy transfer at high efficiency. The individual switches operate at much lower rating and without the attendant high voltage problem.

MEATGRINDER COIL DESIGN

In previous papers[1,2], the merits of the Meatgrinder circuit were described. In particular, it was shown that the opening switch problem is drastically reduced by virtue of the reversibility of the process and that the number of switches, hence the number of Meatgrinder steps, is a function of the efficiency required (the ratio of final to initial energy), mutual coupling, and current multiplication. In a physical system, however, the coupling coefficient cannot be prescribed and is determined by the physical geometry of the coil.

It has been shown that the current gain of the mth step is given by the basic Meatgrinder equation

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1985	**N/A**	**-**

4. TITLE AND SUBTITLE
The Design And Analysis Of A Multi-Stage Meatgrinder Circuit

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Energy Compression Research Corp. 2043 De Mayo Rd., Del Mar Ca. 92014

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
This paper describes the determination of design requirements, performance analysis and design tools used in the design of an 11-step high efficiency high current gain device at the multi -megaj oul e energy 1 evel â¢ In addition to the efficiency improvement when compared with the conventional approach, the total switch power (ie., current x voltage> is reduced from twice the load power to roughly 1/3 the load power. The individual switch power is reduced to 1/18 the load power.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT	b ABSTRACT	c THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

$$\frac{I_{m+1}}{I_m} = \frac{L_{m+1} + L_R + M}{L_{m+1} + L_R} \qquad (1)$$

where L_R is the total remaining inductance commencing with L_{m+2} (see Figure 2). Note that the current ratio depends only on the ratio of the inductances. Consequently the efficiency also only depends on the inductance ratios. In practical applications, the current gain is generally the determining factor in the design of a storage and transfer system. As was shown by Zucker et. al.[1], arbitrarily high efficiency can be achieved by increasing the number of Meatgrinder steps for a fixed value of storage and transfer inductance. Thus the number of steps to achieve the required efficiency can be determined for a given current gain.

A computational procedure has been developed by Energy Compression Research Corporation (ECR) which incorporates the geometry in the inductive coil design to yield real coupling coefficients. An axi-symmetric Elliptic Integral Solver is used to calculate the flux at a point, given a current carrying coil at some other location (see Figure 3). This determines the self and mutual inductances by averaging the flux due to a current in one coil over itself (self inductance) or another coil (mutual inductance). The physical dimensions of the coil sections and the number of turns in each section are determined by solving the circuit equations for the efficiency per step.

11 STEP MEATGRINDER

The 11 step Meatgrinder (see Figure 4) is designed to deliver energy in the 100 millisecond regime to a 100 μH load. The time constant requirements dictate a coil radius of approximately 1.5 meter. The Meatgrinder is composed of 12 coupled inductive elements, with a time constant of approximately 3 seconds. This time constant allows charging of the Meatgrinder from an alternator. The circuit is shown in Figure 5 together with the self and mutual inductance values and resistance values of all the elements in matrix form. The individual coil dimensions, mutual coupling, turn density, and current density are given in Table 1. The Meatgrinder transfers energy to the load inductance in 11 switching operations with 48 percent efficiency, while multiplying the current from 10 kA to 773 kA (See Figure 6). This current level corresponds to 33 MJ in the 112 μH inductor from 69 MJ initially charged in the Meatgrinder. The mass of the coil is 40 tons (40000 Kg) for a copper coil with 2.0 ohm-cm resistivity (for a cryogenically cooled coil the weight is approximately 2.5 tons).

SWITCHES

The Meatgrinder, while providing high current multiplication, transfers its energy to the load inductance in ~100 milliseconds with 11 switching operations. The first five switches (switches 11 through 7 in Table 1) are operated between 10 kA and 100 kA at approximately 50 kV. These will be opened in approximately 15 ms each. The next five (switches 6 through 1 in Table 1) are operated between 100 kA and 770 kA at approximately 10 kV and are opened in approximately 5 ms each. This switching sequence transfers the energy to the load inductance.

The switch requirement is low but they have to operate sequentially. Although a variety of switch candidates apply, preliminary analysis done by ECR shows that an opening switch under development by ECR based on the rupture of a foil by arc quenching gas lends itself well to sequencing and repetitive operation at 10 pps.

CONCLUSION

The design requirements to transfer megajoule energies to inductive loads using the Meatgrinder inductive transfer circuit have been developed. The computational tools to provide a detailed physical description of a design were described. The resulting design, though not optimum, provides advantages in weight, complexity, efficiency, and reliability over conventional approaches.

REFERENCES

1. O. Zucker, et al. "The Meat Grinder: Theorical and Practical Limitations", IEEE Transactions on Magnetics, Vol. Mag-20, No. 2, March 1984

2. O. Zucker and J. Long, "The Meat Grinder, A Reversible Inductive Storage and Transfer System," Pulse Power Conference, Albuquerque, New Mexico, June 1980.

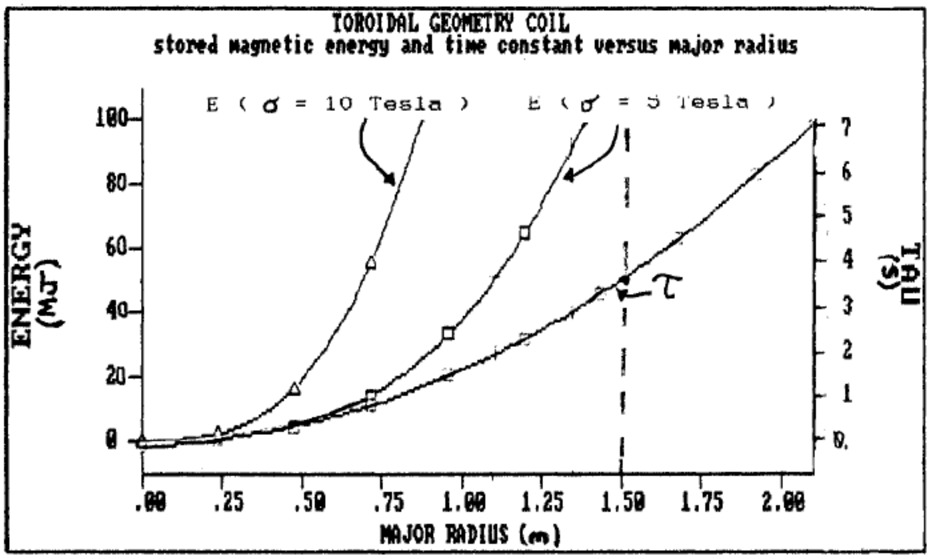


Figure 1. The variation of inductor time constant and stored magnetic energy as a function of major radius.

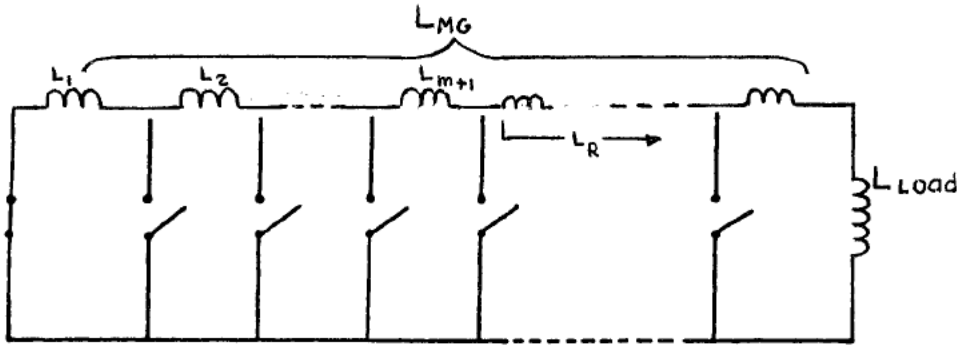


Figure 2. Sequential switching scheme for inductive energy transfer.

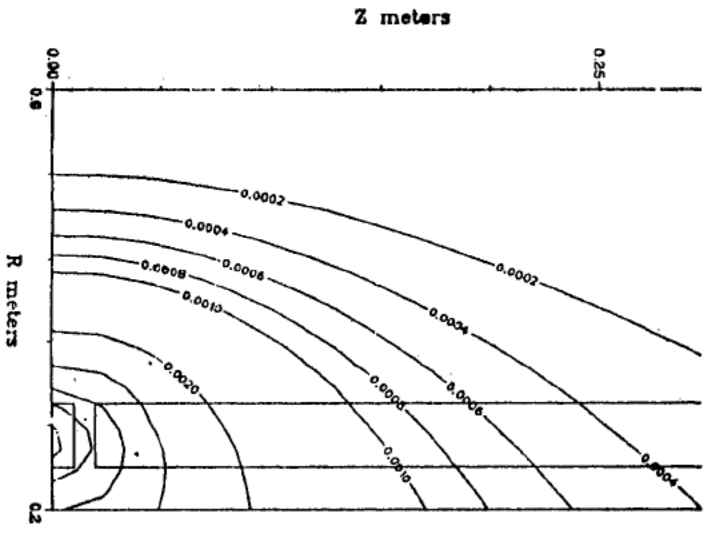


Figure 3. Representative field plot used in the calculations of the self and mutual inductances for the coil design.

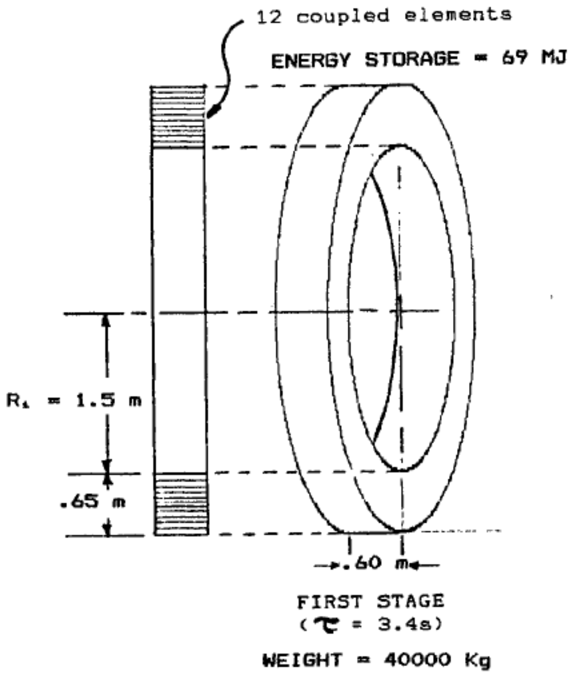
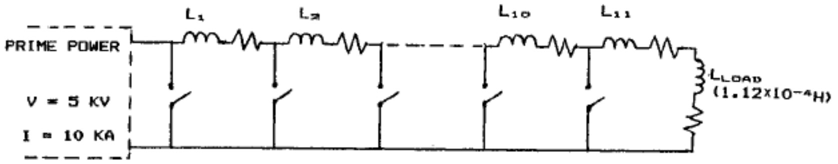


Figure 4. Geometry of the 11 step Meatgrinder



$$\begin{bmatrix} 3.98E-01 & 2.01E-01 & 9.91E-02 & & & & \vdots \\ 2.01E-01 & 1.19E-01 & 6.00E-02 & & & & \\ 9.91E-02 & 6.00E-02 & 3.54E-02 & & & & \\ \vdots & & & \ddots & & & \\ & & & & 1.65E-05 & 1.20E-05 & 1.58E-05 \\ & & & & 1.20E-05 & 9.52E-06 & 1.27E-05 \\ & & & & 1.58E-05 & 1.27E-05 & 1.89E-05 \end{bmatrix}$$

INDUCTANCE MATRIX (11 x 11)

$$\begin{bmatrix} 2.56E-05 & & & & & & \\ & 2.00E-05 & & & & & \\ & & 3.09E-05 & & & & \\ & & & \ddots & & & \\ & & & & 3.32E-02 & & \\ & & & & & 1.08E-01 & \\ & & & & & & 3.57E-01 \end{bmatrix}$$

RESISTANCE MATRIX

Figure 5. Circuit schematic with inductance and resistance values given in matrix form.

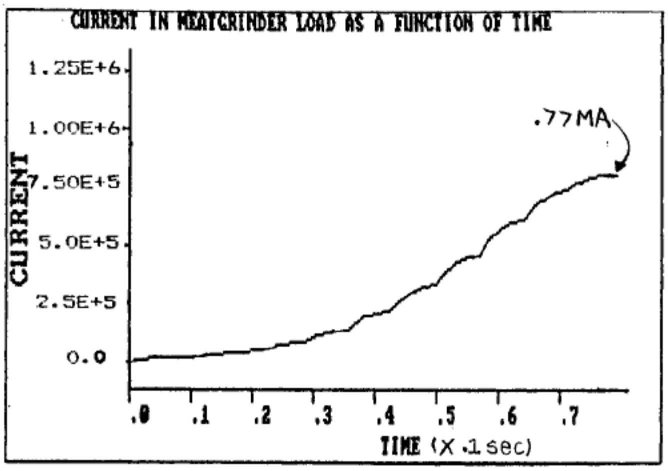


Figure 6. The current in the load has increased form 1×10^4 A to 7.7×10^5A in the 11 step Meatgrinder circuit.

major radius = 1.50 m
length of section = 0.6 m
load inductance = 1.123E-04 H
resistivity = 2.000E-08
load resistance = 9.500E-05
gap between turns = 5.000E-04 m

B = 2.79T
J = 25.8 μA/m^2

step #	turns	total L2 (H)	current (A)	coupling coefficient	L1 (H)	resistance Ω	time constant (s)
0	2.000E+00	1.892E-05	7.730E+05	.000E+00	.000E+00	2.555E-05	1.089E+00
1	1.000E+00	5.391E-05	7.047E+05	9.465E-01	9.543E-06	1.995E-05	1.183E+00
2	2.000E+00	1.260E-04	6.038E+05	9.299E-01	1.656E-05	3.091E-05	1.390E+00
3	3.000E+00	2.838E-04	4.805E+05	9.141E-01	3.548E-05	5.735E-05	1.731E+00
4	4.000E+00	6.700E-04	3.508E+05	9.002E-01	9.328E-05	1.287E-04	2.189E+00
5	7.000E+00	1.738E-03	2.340E+05	8.898E-01	2.875E-04	3.425E-04	2.644E+00
6	1.300E+01	4.972E-03	1.448E+05	8.839E-01	9.552E-04	1.021E-03	2.955E+00
7	2.300E+01	1.522E-02	8.558E+04	8.820E-01	3.204E-03	3.200E-03	3.115E+00
8	4.100E+01	4.839E-02	4.937E+04	8.824E-01	1.068E-02	1.024E-02	3.198E+00
9	7.300E+01	1.572E-01	2.812E+04	8.834E-01	3.553E-02	3.316E-02	3.255E+00
10	1.300E+02	5.177E-01	1.590E+04	8.846E-01	1.188E-01	1.084E-01	3.304E+00
11	2.310E+02	1.723E+00	8.945E+03	8.857E-01	3.995E-01	3.572E-01	3.353E+00

Table 1. A detailed design of the inductive transfer system. The physical geometries of each inductive element are given as the number of turns, inductance, resistance, radial thickness, etc. The current is shown to rise from 8,945 A to .77 MA with a time constant of 3.35s. The magnetic field and current density is 2.79 Tesla and 25.6 μA/m^2.